# State of Play of Low-Cost Sensors for Monitoring $PM_{2.5}$

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# Foreword

Air pollution and awareness amongst the public has reached its zenith, however, the measurement and its communication have still remained a major challenge. Until just a decade ago, air quality measurement required a trained workforce and complex infrastructure. With recent technological advances, however, lower-cost air pollution sensors help democratize access to data, making the causes of pollution more visible, tangible, and personal. Although the quest to identify its suitable role still needs to be addressed.

Air quality research is one of the major R & D division of CSIR-NEERI. The monitoring of pollutants is aimed towards regulatory compliance and support regulators for establishing a strong monitoring network. In the 1970s, BARC, National Productivity Council (NPC), and NEERI were tasked to design India's first air quality monitoring equipment. Before that, there were dust charts, and Ringelmann's charts used to study the plume from the stack and decide on pollution levels. CSIR NEERI journey towards understanding of science and technology has continued even today with advanced analysers for physical and chemical speciation of particulate matter; gaseous analysis, analysis of molecular markers besides meteorological measurements

In recent times, an air quality monitoring network can provide a high spatial resolution; real-time information is essential for developing management strategies for air quality improvement. National Environmental Engineering Research Institute (CSIR-NEERI) has deployed a Sensor-based Wireless Air Quality Monitoring Network to monitor real-time particulate matter ($PM_{10}$ and $PM_{2.5}$) concentrations in a highly urbanized megacity, Delhi, the capital of India. It has provided various insights and suggests that the sensor-based network (low/affordable cost) can be successfully operated to get the real-time air quality levels in an urban area.

Our vast geography and the prohibitive cost of Continuous Ambient Air Quality Monitoring Stations (CAAQMS) leave a few blank spots. These data gaps may drastically impact our action plans for many such areas. NEERI is continuing the research in this area to understand the feasibility of using Lower Cost Air Quality Sensors to augment the data gaps.

In recent times, Lower Cost Sensors are being extensively researched and studied by various National & International institutions. The data sets have been instrumental in understanding pollution hotspots. Hence, it is of interest to multiple stakeholders – policymakers, academia, citizens, and regulators. However, few challenges need to be considered before their deployment - higher measurement errors, complex and unstable calibration, and durability concerns. Deployment in Delhi at 10 ambient locations and also in Mumbai near a waste management sites, indicates that with increasing understanding these tools will become more robust with time.

Towards this effort, NEERI, IndAIR, the University of Texas at Austin, and University of California, Berkeley have put together a comprehensive report addressing some of the Lower-cost sensor experiences. The report has also provided technical insights about various lower-cost sensors deployed at multiple study locations – rural & urban settings. This report will support India's flagship air-quality management initiative - the National Clean Air Plan (NCAP). The continued better understanding of air quality in spatio-temporal domain will be immensely useful.

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## Executive Summary

Major data gaps are a key factor impeding effective air pollution management in India. Considering fine particulate matter ($PM_{2.5}$) air pollution, which is the air pollutant that poses the largest risk for ill-health and death in India, there are only a few hundred existing continuous regulatory monitoring stations currently active in India. On the basis of Central Pollution Control Board Guidelines, Brauer et al (2019)[1] suggest that 1600-4000 monitoring sites – a more than 10x increase – might be needed to adequately monitor $PM_{2.5}$ air quality in Indian cities. However, traditional regulatory-grade air pollution monitoring sites are expensive, with an approximate procurement and installation cost of INR 1 crore ($130,000 USD) or higher. The potential for lower-cost sensors technologies to empower citizens, policy analysts, scientists, and regulators is therefore of keen interest. At the same time, lower-cost air pollution sensors raise a host of technical challenges – higher measurement errors, complex and unstable calibration, and concerns about durability. Stemming from these technical challenges, regulators and scientists alike often approach air sensors skeptically or with tentative acceptance, while citizens may be confused by the proliferation of multiple official and unofficial measurement approaches.

This brief report covers the following topics:

- Particulate air pollution: its sources, composition, and atmospheric behavior.
- Regulatory measurement technology for $PM_{2.5}$
- The operational principles of optical $PM_{2.5}$ measurement technology, including low-cost sensors
- Considerations for evaluating the performance of PM sensors in India, especially through field performance evaluations.
- Which applications are today's $PM_{2.5}$ sensors well-suited for in India?

Broadly, the report suggests that low-cost $PM_{2.5}$ sensors may not yet be suitable for a variety of key applications, yet also concludes that low-cost sensors can already provide valuable qualitative information about air quality in settings where other more robust measurements are not available.

- With careful attention to calibration in a research or routine monitoring environment, a low-cost sensor can often provide a moderately precise and accurate (±15-30%) determination of $PM_{2.5}$, and can provide valuable information about the spatial and temporal patterns of air pollution.
- Many low-cost $PM_{2.5}$ sensors today have good unit-to-unit precision, especially when new. This means that any two sensors exposed to similar environmental conditions will generally report similar values. In many urban environments around the world, lower-cost $PM_{2.5}$ sensors are densely deployed in crowd sourced networks (e.g., the PurpleAir network), and these dense networks can approximately reproduce the spatial patterns of air pollution in cities. Notably, in most circumstances, spatial gradients of $PM_{2.5}$ in urban areas are relatively modest (about as large as the measurement uncertainty of a sensor), but these sensor networks are capable of resolving the movement of pollution through an urban environment in real-time.

[1] Michael Brauer, Sarath K. Guttikunda, Nishad K A, Sagnik Dey, Sachchida N. Tripathi, Crystal Weagle, Randall V. Martin, Examination of monitoring approaches for ambient air pollution: A case study for India, Atmospheric Environment 216, 2019, 116940.

- Where a precise and absolute determination of air quality is required, low-cost sensors are generally not yet suitable for widespread use. Such applications might include regulatory measurements to evaluate compliance with air quality standards.
- While low-cost $PM_{2.5}$ sensors can be calibrated to reasonably match official measurements, these calibrations tend to drift over time, and may also be quite inaccurate when atmospheric conditions suddenly change (e.g., during a dust storm, wildfire, or other severe pollution event). As such, while a low-cost sensor can offer an approximate measure of the air quality index (AQI), it may be prone to rather large bias during unusual air pollution events.
- Low-cost sensors are already capable of offering useful qualitative information that may be useful for informing the public during air pollution events. A spatially dense sensor network can provide useful information to common questions. For example, a citizen concerned about whether the air outside is clean enough to take a walk can get a sense of how much cleaner or more polluted air might be at one instant compared to a few hours before. Likewise, a dense sensor network can highlight zones of a city that may be relatively more or less polluted, which may be useful if one is in search of cleaner air to exercise. While these spatial and temporal gradients of pollution may be small during ordinary conditions, during extreme pollution events these pollution differences in space and time may be quite dramatic and very easily discerned with a crowd-sourced sensor network.

The overall conclusion of this report, therefore, is that low-cost sensors offer a useful and complementary approach to measuring $PM_{2.5}$ air pollution in India that can contribute to filling critical data gaps. Ongoing efforts to characterize, validate, and refine the performance of low-cost sensors can contribute to the increasing acceptance of this promising new technology in India.

## 1. What is Fine Particulate Matter?

Fine particulate matter ($PM_{2.5}$) is defined as the volumetric mass concentration of suspended particles with aerodynamic diameter less than 2.5 μm. Within this seemingly precise description lies a rich set of subtleties.

$PM_{2.5}$ is both a *primary* pollutant (fine particles can be directly emitted) and a *secondary* pollutant (particles can be formed from the emissions and transformation of precursor emissions, including organic compounds, ammonia, and sulfur and nitrogen oxides). Examples of processes that generate primary $PM_{2.5}$ include combustion (which often produces elemental and organic carbon, visible to the naked eye as white, black, or bluish smoke, as well as condensed metals and other fuel impurities) and mechanical/abrasive processes that produce fine mineral or metal dust (e.g., construction, wear of brakes and tires). Secondary $PM_{2.5}$ formation occurs as a result of atmospheric chemical reactions that convert gases into particles. Depending on the atmospheric conditions, secondary formation processes can include both particle *nucleation* (new particles forming from the collision of multiple gaseous molecules) and particle *growth* (gaseous vapors condensing onto existing particles, causing them to grow).

The composition of $PM_{2.5}$ particles is complex, often incorporating both liquid and solid materials. Components of $PM_{2.5}$ particles can include condensed organic compounds, elemental carbon and soot, inorganic salts (especially ammonium sulfate and ammonium nitrate), metals, and a wide range of crustal minerals. Because some compounds within $PM_{2.5}$ have a strong affinity for water (that is, they are *hygroscopic*), fine particles often also contain liquid water. Particle composition is also highly dynamic in space and time. Just as particles can increase in size by condensational and/or coagulative growth so too can particles shrink by the evaporation of water and semivolatile organic material.

Atmospheric particles vary over a vast range of sizes. The smallest particles formed by fresh nucleation are merely clusters of a small number of molecules, and are only slightly larger than 1 nanometer (nm, $10^{-9}$ m) in diameter. Large dust and pollen particles are up to 100,000 times larger in diameter, with characteristic diameters on the scale of 10-100 μm ($10^{-5}$ to $10^{-4}$ m). A common (but imprecise) assumption is that particles are approximately spherical in geometry. For a spherical particle of uniform composition, the volume scales with the cube of the diameter, such that a 1 μm spherical particle is 1000 times heavier that a 0.1 μm spherical particle. Within the $PM_{2.5}$ size fraction, particles in the size range from 0.1 μm to 2.5 μm contribute most of the particle mass. (In many cases, there will also be a vast number of particles smaller than 0.1 μm, sometimes referred to as ultrafine particles (UFP) or nanoparticles. In most circumstances, these ultrafine particles will be too small to contribute much to the $PM_{2.5}$ mass, but they can dominate the total number count of particles present in the atmosphere).

Figure 1 shows an example of a typical particle size distribution from a polluted urban atmosphere. The $PM_{2.5}$ mass distribution often has multiple "humps" or "peaks", but very typically, the peak of the $PM_{2.5}$ mass distribution is found somewhere around 0.3 μm in diameter. This mode of the distribution is often referred to as the "accumulation mode", and it is generally formed by the condensation of secondary products of atmospheric chemistry onto preexisting particle nuclei. Very poorly performing combustion processes (e.g., wood bonfires)

can also produce accumulation mode particles. Ultrafine particles, (typically < 0.1 µm or < 100 nm in size) are often the result of fresh combustion activity and may contribute up to 10-20% of the $PM_{2.5}$ mass. A subset of the $PM_{2.5}$ mass typically falls in the size range of 1-2.5 µm. This larger part of the $PM_{2.5}$ spectrum can come from a wide range of sources, including crystalline material (e.g., fine dust from construction or sand storms, or vehicle brake and tire wear), metals processing, and atmospheric chemistry. Finally, many of these mechanically generated particles make up the *coarse fraction* of the particle size distribution – particle mass in the particle size range of 2.5 to 10 µm. This coarse fraction accounts for the difference in particle mass between $PM_{2.5}$ and $PM_{10}$ (particles < 10 µm in aerodynamic diameter).

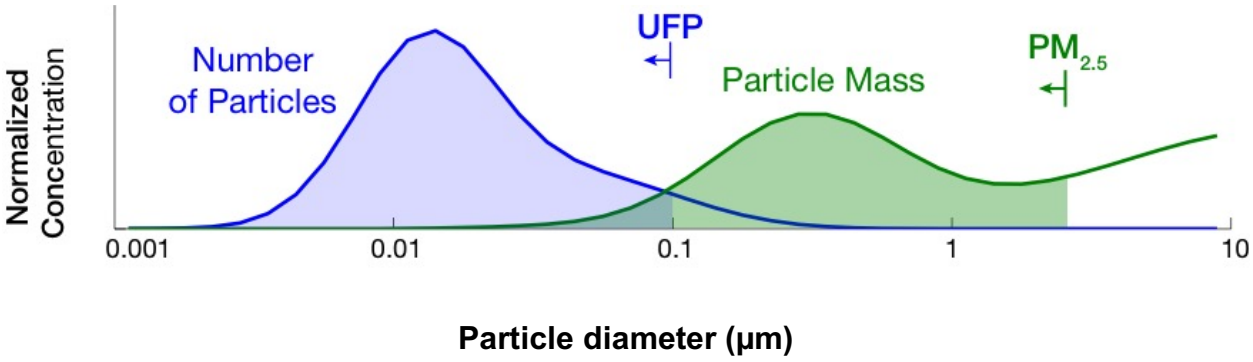



**Figure 1.** Example of a distribution of particle sizes for a polluted urban atmosphere. The same particle size distribution is shown in two ways. The blue "number distribution" shows the frequency distribution of particle number count as a function of their diameter, while the green "mass distribution" shows the frequency distribution of particle mass as a function of particle diameter.

## 2. How is $PM_{2.5}$ measured in regulatory settings?

The reference technique for measuring $PM_{2.5}$ is generally a *gravimetric measurement* – that is, measuring the mass of suspended particles contained in a known volume of air passed through a filter. For example, the U.S. EPA specifies a Federal Reference Method (FRM) for the gravimetric measurement of $PM_{2.5}$. This FRM specifies details such as:

- The air flow rate at which $PM_{2.5}$ must be sampled.
- The technique by which particles smaller than 2.5 µm are separated from larger particles.
- The type of filter to be used for particle sampling.
- Handling and pre-conditioning requirements for samples.
- The temperature (T) and relative humidity (RH) at which filters should be weighed. For example, before weighing, filters are to be pre-equilibrated at specified T and RH (typically 35-40%) for a minimum of 48 hours.
- The type of equipment and sample handling processes that should be used for filter weighing.
- Quality assurance and quality control procedures (QA/QC).
- Siting characteristics for the measurement.

Each of these details can profoundly affect the determination of particle mass. For example, the weight of particles collected on a filter is strongly dependent on the humidity of the air (more humid air will lead to heavier filters as water absorbs into hygroscopic particles) and the temperature at which the filters are maintained (if filters are over-heated, semivolatile material can evaporate off the filters).

By ensuring a consistent process, the FRM ensures highly reproducible measurements. However, gravimetric measurements have key limitations. By virtue of being time-integrated samples, filter samples lack time resolution. Manual collection, handling, and weighing of filters is labor-intensive, repetitive, and requires great care to result in high-precision measurements. Because the analysis technique is offline, filter measurements do not provide real-time data. Thus, alternative continuous measurement techniques can complement FRM measurements. Some alternative techniques can be certified to provide results that are nearly equivalent in terms of data quality to reference methods. For example, the US EPA has a procedure under which an alternative measurement technique can be certified as a "Federal-Equivalent Method" (FEM) for measuring $PM_{2.5}$. Two widely deployed FEM-certified measurement techniques for $PM_{2.5}$ are:

- **Beta Attenuation (BAM):** Particles are sampled at a known flow rate and continuously collected on a filter tape. As the particles deposit on the filter tape, a spot of collected particles builds up. A radioactive carbon-14 source emits a beam of beta radiation that is focused through the filter spot on a radiation detector. As particles build up on the filter spot, the beta radiation is more strongly attenuated, and the attenuation on the filter is used as a proxy for an increase in the mass loading on the filter.

- **TEOM (Tapered-Element Oscillating Microbalance) –** Air is sampled at a known flow rate and particles are deposited on a resonating element. As the particles deposit, the mass on the resonating element increases, altering the resonant frequency of the element. This increase in mass loading is used as a determination of the mass concentration of particles.

Each of these FEM techniques can provide reasonably reliable and reproducible 24-hour averaged $PM_{2.5}$ measurements continuously and automatically. The instruments are also configured to report data at an hourly frequency, which can be quite helpful for scientific studies and for public information purposes. However, measurements are generally less certain for short averaging periods (e.g., shorter than 1 hour). In addition, both of these FEM techniques have known measurement artefacts. For example, a TEOM element is often maintained at a high temperature to prevent excessive condensation of water vapor. As a consequence of this high temperature, semivolatile nitrate particles can be lost to evaporation, which will result in a negative measurement artefact. Thus, when multiple measurement techniques are used in parallel, there may be complex and meaningful differences between competing techniques (e.g., Figure 2).

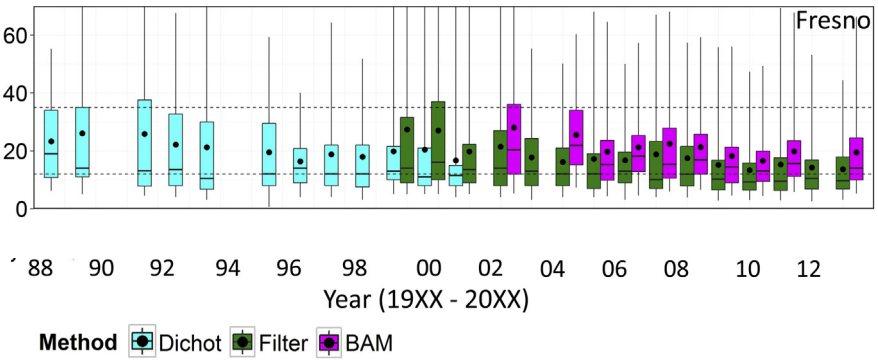



**Figure 2.** $PM_{2.5}$ mass concentrations (μg $m^{-3}$) measured in three different ways in Fresno, California, 1988 – 2013. Note that some techniques result in consistently higher measurements than others. Source: Tao and Harley, *Atmospheric Environment* 98 (2014) 676-684.

## 3. Optical measurements of $PM_{2.5}$

Inexpensive light-based sensors have emerged as a popular way to estimate $PM_{2.5}$ concentrations at a fraction of the cost of reference-certified instruments. Indeed, when considering the broad range of air pollutants for which low-cost sensor technologies are under development, the technology for inexpensively sensing $PM_{2.5}$ with light scattering is among the most well-understood and widely deployed. This section provides a brief overview of the fundamental physical considerations of optical particle measurements.

Our everyday experience reveals that atmospheric particles interact with visible light. A smoke-belching bus might produce a black plume of smoke – with the blackness indicating the presence of light-absorbing soot particles that prevent light being transmitted through the plume. On heavily polluted days, ambient particles might create a haze that limits the range at which we can see. Here, the visibility impairment we perceive is the result of ambient light being scattered off particles towards our eyes, interfering with the light reflected off the scene that we wish to see. The more particles in the atmosphere, and the farther the away the scene that we wish to see, the greater the impairment of our ability to clearly perceive the scene.

$PM_{2.5}$ particles effectively scatter visible light in part because the wavelength of visible light (green light has a wavelength of ~ 500 nm) is very similar to the diameter of $PM_{2.5}$ particles. For particles that are much smaller than the wavelength of light (e.g., particles smaller than 300-500 nm), considerably less light scattering occurs. Two common types of optical scattering measurements have been used in atmospheric and aerosol science for decades:

- Single particles may be counted on the basis of light scattering. An *optical particle counter* (OPC) measures the number concentration of particles by passing a thin stream of particles through a focused light beam (usually a laser). When a single particle passes through the laser beam, it scatters light. Some of the scattered light is collected by a mirror and focused onto a detector. The pulse of light is measured by a detector, and counted as a particle (Figure 3). The volumetric number concentration of particles (e.g., number of particles per cubic meter of air) is determined by dividing the count frequency (counts per second) of particles by the measured flowrate of air (cubic meter per second).

The OPC can provide a nearly instantaneous and reasonably linear measurement of particle number counts for particles that are sufficiently large to reliably scatter laser light. However, for very high particle number concentrations, multiple particles may arrive in the laser beam at once, and be counted as a single particle. These *particle coincidence errors* can result in systematic undercounting of particles under polluted conditions. Over time, the performance of an optical measurement system can be degraded if the optical components become fouled by particle deposition. A partial solution to this fouling problem can be obtained through the use of "sheath air flow" – encapsulating the sampled particle beam to be measured inside an annular flow of purified air that keeps the sample air confined in a narrow beam that does not touch the optics.

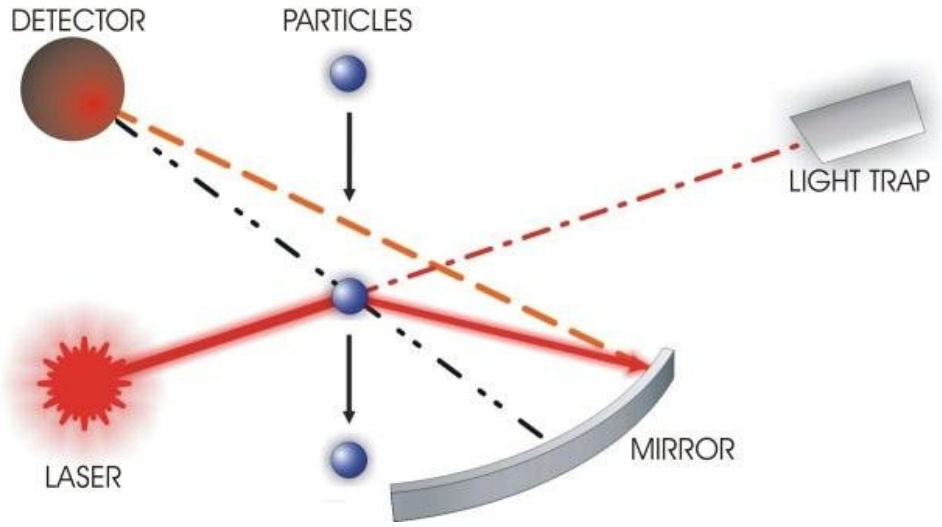



**Figure 3.** Simplified schematic of a single-particle optical particle counter.

A critical limitation of single-particle optical counting for measuring $PM_{2.5}$ mass is that mass concentration has only a weak correlation with number concentration. All else being equal, a larger particle will have more mass than a small particle – but if each particle is counted equally, then the number count will be a poor proxy for the mass concentration. One approach used to estimate the mass concentration in an OPC-type instrument is to attempt to gain information about each particle's size at the point at which it is being counted. If the size could be reliably determined, then the mass concentration could be estimated. Of course, size is an imperfect proxy for mass – the shape and density of a particle will affect the relationship between its diameter and its mass. As a result, a critical challenge is that it is very difficult to precisely measure a particle's size on the basis of its light-scattering properties.

Some optical instruments attempt to measure particle size using a branch of optical physics known as *Mie theory.* For a particle of known geometry and composition, the intensity with which it will scatter incident light can be estimated by Mie theory. Thus, an optical particle counter may attempt to infer the size of a particle based on the relationship between the scattered light observed and the intensity of the laser beam light

source. However, a critical challenge is that the Mie scattering efficiency of a particle depends not merely on particle size, but also on a wide range of other physical and environmental parameters, including:

- The relative humidity at which the measurement is made, and the amount of water vapor absorbed onto the particle.
- The geometry of the particle.
- The composition of the particle (which affects its ability to scatter light, its refractive index, and the degree to which it absorbs water vapor).

- An alternative optical measurement approach uses an instrument called an *integrating nephelometer*. Here, scattering is measured for an entire population of particles that are introduced into a highly polished optical chamber. The instrument measures the relationship in intensity between the light put into the optical chamber, and the light scattered off the particles. Two distinct nephelometer-type designs exist – a so-called "photometer" that measures light scattering at a specific viewing angle, and an "integrating" nephelometer that collects light scattered over all directions. This distinction is important because light scattering from particles is directional.

  From this measurement of light scattering, a scattering coefficient for the full population of particles can be determined. This scattering coefficient may be of direct relevance for many research applications, such as determining how ambient PM affects Earth's radiative energy balance. But scattering is not a perfect proxy for $PM_{2.5}$ mass. All else being equal, a population of particles that scatters more light will also contain more $PM_{2.5}$ mass. But of course, all else is not always equal.

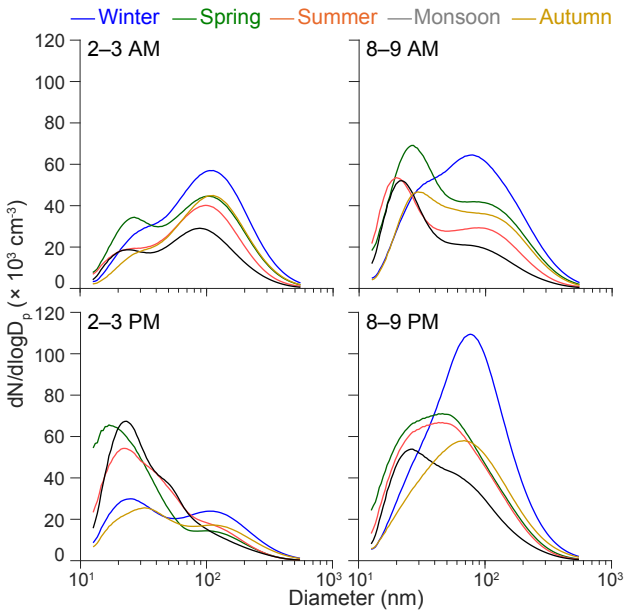



**Figure 4.** Example of ambient particle number size distributions between 12 and 560 nm measured at the Indian Institute of Technology, Delhi in different seasons and times of day in

2017-2018. Particle number size distributions vary dramatically among seasons and by time of day. *Source:* S. Gani et al., Atmos Chem Phys, 2020.

Finally, it is worth noting that some sensors that describe themselves as "optical particle counters" and/or present an estimate of size-resolved PM (e.g., the Plantower PMS sensors) actually are not rather single-particle instruments, but rather behave more like photometers. Hagan et al (2020) present a useful review that distinguishes between these two sensor system types.[2]

## 4. Calibration of Optical Instruments to Estimate $PM_{2.5}$

To make an estimate of $PM_{2.5}$ mass, optical instruments are often calibrated by making a set of assumptions about the particle size distribution, geometry, composition, and relative humidity. With careful calibration for a well-constrained set of conditions, optical instruments can provide a reasonably quantitative estimate of $PM_{2.5}$ mass concentrations. However, environmental conditions are often extremely dynamic. The size distribution of freshly emitted particles is completely different than that of atmospherically aged pollution, and this particle size distribution can be sharply different in different season (see Figure 4 for an example from New Delhi). Fresh particles may be only 10-150 nm in diameter, and too small to efficiently scatter light. The composition and light-scattering efficiency of particles depends strongly on the source of the particles, so that fresh diesel exhaust will have an entirely different scattering-to-mass relationship than would secondary ammonium sulfate produced from atmospheric chemistry. Finally, the humidity may change rapidly with weather or if the measurement is conducted at multiple locations. Thus, the overall challenge is that while an optical particle instrument can be well calibrated to $PM_{2.5}$ for a particular set of environmental conditions, that calibration may be very difficult to generalize to the full range of real-world conditions for which one might wish to apply these sensors.

A variety of different approaches exist for calibrating light-scattering optical instruments to estimate $PM_{2.5}$ mass. In broad terms, these calibrations fall into lab-based and field-based calibrations. For a lab-based calibration, sensors can be evaluated and calibrated against particles of known size and composition, and the response of the sensor design to a variety of environmental interferences (humidity, temperature, other pollutants) can be systematically investigated. However, a challenge with lab-based calibration is that the full range of real-world conditions is difficult to simulate, and real-world particles are not always well-approximated with laboratory-generated mixtures. For a field-based calibration, a light-scattering instrument is co-deployed in parallel with a real-time reference instrument (often a FEM reference instrument such as a BAM or TEOM). The field calibration is determined by developing a univariate statistical relationship between the reference instrument and the light-scattering instrument. A more complex calibration scheme might incorporate additional measurements of other environmental parameters that are incorporated into a multivariate calibration. Key challenges with a field calibration include (i) generalizability to multiple sites, and (ii) an imperfect ability

[2] Hagan, D. H. and Kroll, J. H.: Assessing the accuracy of low-cost optical particle sensors using a physics-based approach, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2020-188, in review, 2020.

to understand the cause of an imperfect relationship between reference and optical measurements.

In the case of lower-cost sensors, numerous additional design, calibration, and validation challenges arise. For example, while a scientific-grade OPC may be deployed with additional equipment that provides a precise size separation of $PM_{2.5}$ from coarser particles, most low-cost sensors lack the ability to physically size-separate particles into the $PM_{2.5}$ fraction. In a scientific sampling scheme, humidity artefacts can be addressed to some degree by designing sampling inlets that intentionally manipulate the sample temperature or the gas-phase partial pressure of water vapor. In a low-cost sensor, humidity control is generally not easy to perform. For a low-cost OPC, air flow rates may be difficult to precisely control or measure, yet the air flow rate forms the fundamental denominator that determines the particle concentration from the optical signal. Reference grade instruments can be designed with complex plumbing to produce a purified sheath air flow that protects the long-term integrity of optical systems, but this is more difficult to achieve in a small sensor.

## 5. Sensor Performance Evaluation and Calibration in India – Research and Future Needs

India experiences a very wide range of environmental conditions. Particle concentrations range from quite clean (e.g., pristine environments, monsoon conditions) to some of the most polluted conditions anywhere on the planet (e.g., biomass burning episodes in the North Indian autumn and winter seasons). Particle composition and size distribution is quite variable in time and by microenvironment (e.g., rural, urban, by neighborhood, indoor vs. outdoor). Indoor environments may have quite different particle composition and size distributions than the outdoors, especially when combustion sources or air purifiers are present. Typical humidity levels differ dramatically by region, and between the wet and dry seasons. For measuring $PM_{2.5}$, the baseline expectation ought to be that light-scattering particle sensors could have very different performance and calibration characteristics across this wide range of conditions.

As an illustrative example, our research group recently conducted a relatively simple performance evaluation of two identical Purple Air model PAII-SD sensors at the US Embassy site in the diplomatic enclave of Chanakyapuri, New Delhi. Each PAII-SD contains two identical Plantower PMS5003 laser optical particle counters, which provide size-resolved particle counts for 0.3, 0.5, 1.0, 2.5, 5.0 and 10μm particles as well as the manufacturer's estimate of $PM_{2.5}$ mass concentration. We evaluated the correlation of the default $PM_{2.5}$ output against contemporaneous measurements of $PM_{2.5}$ from the US Embassy's EPA FEM monitor (MetOne Model BAM-1020). We situated the two PurpleAir sensors at a height of ~ 3 meters at approximately 10 meters distance from the FEM monitor inlet. The PurpleAir sensors operated continuously from July 2018 to February 2019. Each PurpleAir reports the simultaneous measurement every 80 seconds of its two particle counters, which are termed "Sensor A" and "Sensor B". With two PurpleAir units, we thus obtained sensor measurements for four particle counters, termed A-1, B-1, A-2, and B-2. Figure 5, below, shows the comparison of these instruments during this evaluation.

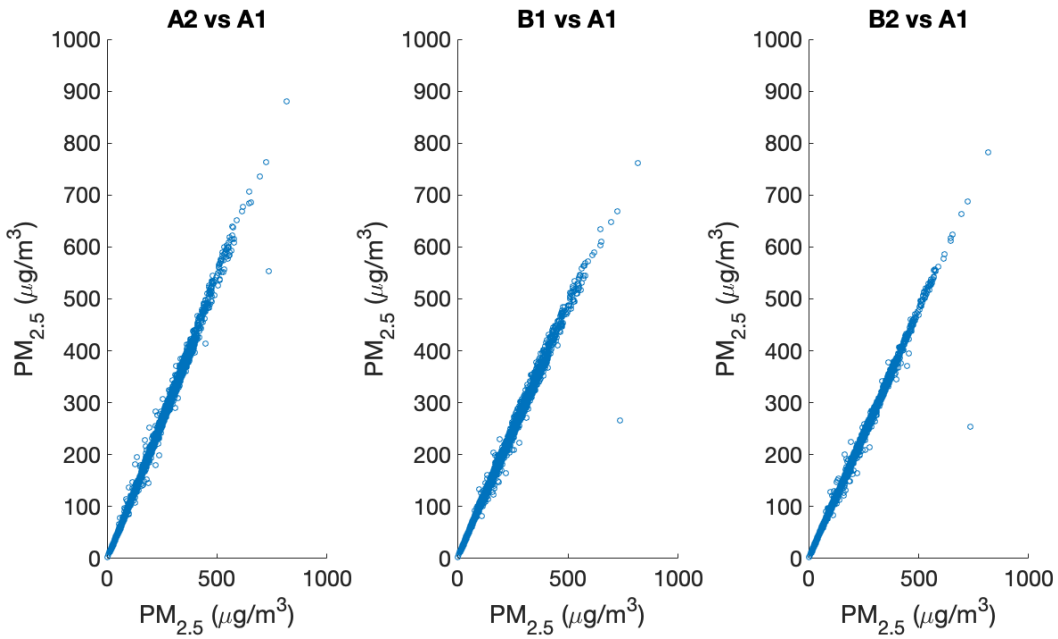



**Figure 5.** Hourly-averaged readings of Sensor A1 against three other sensors (B1, A2, B2) from July 2018 to February 2019 at the US Embassy site.

The data in Figure 5 suggests that each Plantower sensor in the PurpleAir produces a concentration estimate that is highly correlated with the other sensors outputs: all of the measurements are tightly clustered along a single line over conditions spanning a very broad range of concentrations (~ 0 – 750 µg $m^{-3}$ hourly average). Only a very small number of hourly measurements fall outside of this clearly defined line, implying that the PurpleAir produces highly reproducible measurements. However, careful analysis shows that the slopes of the pairwise relationships among sensors varies by ±10-15% among individual sensors. In other words, some sensors consistently read slightly higher or lower than other sensors, but they all increase and decrease in unison.

Of course, it is also critical that a particular type of low-cost sensor not only have good precision (i.e., measures the same thing every time), but also that it has good accuracy relative to a reference method (i.e., it produces a *correct* or *unbiased* result). Figure 6 shows one of the four sensors compared against the BAM measurement. Interestingly, the degree of scatter in the BAM-PurpleAir relationship is dramatically lower for a 12 hour averaging period. We speculate that this result may arise in part because 1 hour-average measurements for a BAM sensor can be quite noisy. Over the full duration of this evaluation study, 12-hour-average concentrations for the PurpleAir tended to be ~20-25% higher than the BAM on average. However, this performance bias appears to be seasonally dependent. The greatest upward bias happened during autumn and winter months (i.e., October to February), while the PA sensor tended to under-estimate $PM_{2.5}$ during the monsoon period (i.e., July to September). This is a common performance characteristic of low-cost sensors: their response to $PM_{2.5}$ is not always consistent in time.

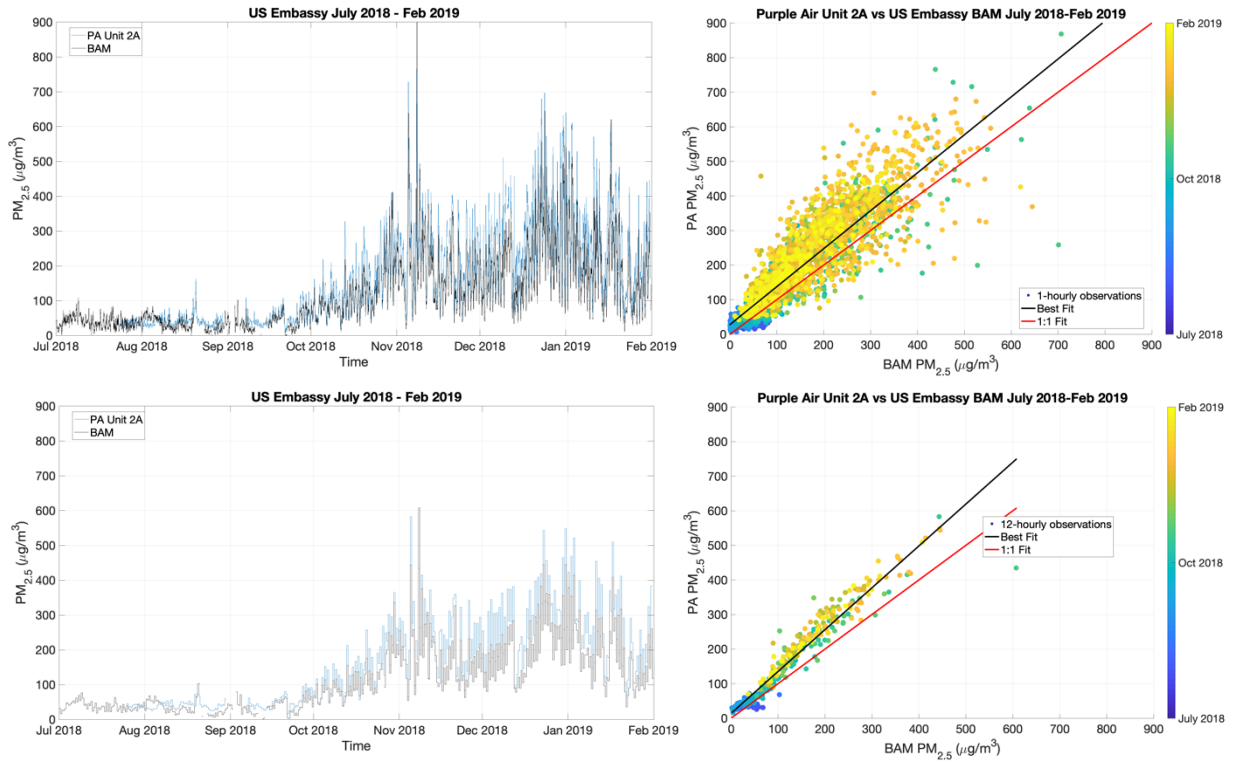



**Figure 6.** Hourly (upper row) and 12-hourly (bottom) average concentrations for PurpleAir sensor #2A vs. US Embassy BAM reference monitor, July 2018 – February 2019. Left plots show time-series data, right plots show scatter between BAM and Purple Air sensors.

Careful scrutiny of the time series Figure 6 suggests that the relationship between the PurpleAir and the BAM at the Embassy site was somewhat inconsistent in time. For example, in successive weeks in August and September 2018, the PurpleAir alternatively under-reported and over-reported the BAM's $PM_{2.5}$ concentrations (and yet the PurpleAirs were all highly consistent with each other over this time period). During some extreme pollution episodes in November 2018, the PurpleAir sensor reported $PM_{2.5}$ concentrations that differed from by the BAM by more than 150-200 $\mu g\ m^{-3}$ – and in either direction. Clearly, even if the overall picture that emerges from a low-cost sensor is a reasonably reproducible (if biased) performance, considerable uncertainty may remain for shorter time periods.

Similar results have been observed with other light-scattering $PM_{2.5}$ sensors all over the world. One implication of this finding is that the "calibration factor" on any optical sensor might be quite variable even from day-to-day or week-to-week. Why does this result arise? A likely explanation is that the optical properties of particulate matter (e.g., size distribution, composition, volumetric density, humidity-response) change frequently in urban areas, even at a given location, and so the relationship between a sensor's response and true $PM_{2.5}$ mass will be variable in time. Hagan et al (2020) note that for a nephelometer/photometer sensor such as the Plantower / PurpleAir that is not capable of directly measuring the particle size distribution, shifts in the ambient particle size distribution can result in substantial shifts in the calibration factor of the sensor.

Figure 7 presents additional evidence about the variable response of a sensor by time of day. As this diurnal plot indicates, all four low-cost sensors reported very similar patterns by time of day.

The difference between the highest-reading and lowest-reading units averaged about 20 µg $m^{-3}$ during the most polluted hours of the day. The diurnal profile of the BAM readings was broadly similar (high in the early morning, low in mid-afternoon) to the low-cost sensors, but with much lower concentrations at night and in late afternoon – and yet higher readings in the mid-mornings. Given that the particle size distributions in Delhi shift by both time of day and season (Fig 4), this result makes sense. It does pose challenges for comparing low-cost sensor readings at different times of day.

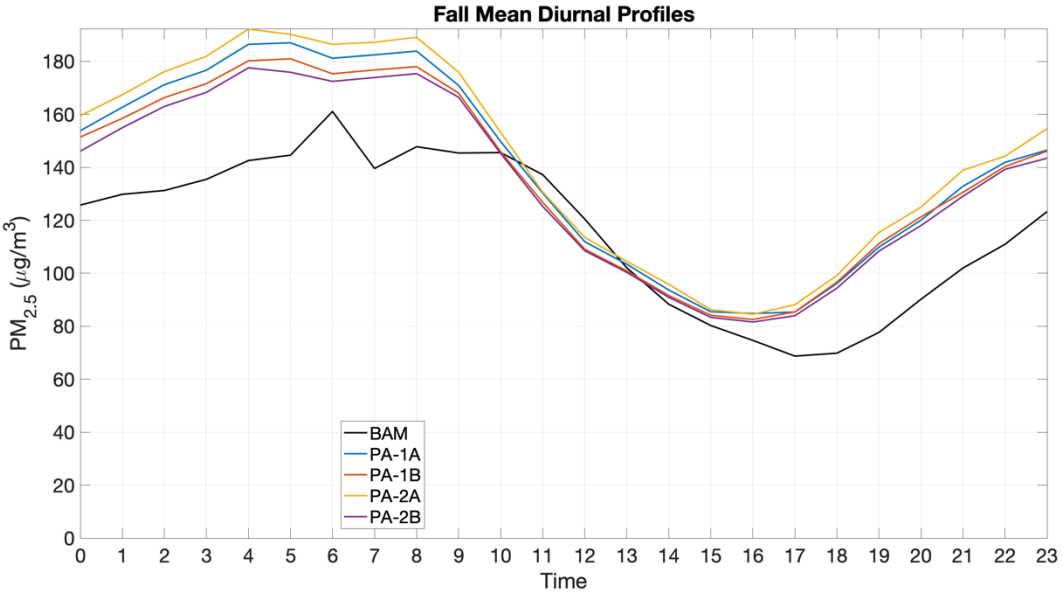



**Figure 7.** Diurnal plot: Average $PM_{2.5}$ concentrations by hour of day during Autumn 2018 reported by Embassy BAM and four Plantower PMS5003 sensors in two PurpleAirs.

## 6. Recommendations for future sensor performance characterization in India

Future studies might conduct a more systematic evaluation of low-cost sensor performance at multiple sites and with more detailed instrumentation that can probe the underlying reasons why low-cost sensors perform as they do. A detailed real-world field characterization of low-cost sensor performance might include the following types of measurements:

- **Reference measurements of $PM_{2.5}$ mass:** Ideally, a site would be equipped with both a FEM mass monitor (for hourly $PM_{2.5}$ measurements) as well as a FRM sampler equipped for 12- or- 24-hour average filter measurements that could be used for both mass measurements as well as subsequent chemical analysis. Because beta-attenuation monitors are currently the most widely used real-time $PM_{2.5}$ instruments in India, BAMs may be the most logical choice for a FEM instrument. It should be noted that BAM monitors, while quite accurate in terms of reporting 24-hour average $PM_{2.5}$ mass concentrations, can be rather imprecise on an hourly time basis (as shown in Fig 6).

- **Particle Size Distribution:** Continuous measurements of particle size distribution from ~ 10 nm – 10 µm. For particles in the 10 nm – 600 nm size range, sizing is most

routinely done on the basis of electrostatic mobility (e.g., using a Scanning Mobility Particle Sizer). For particles in the 300 nm – 10 μm size range, direct measurement of aerodynamic diameter (e.g., via an aerodynamic particle sizer) is the standard technique. This technique provides a reasonably robust estimate of the number size distribution, from which the volume and mass size distribution can be estimated. To provide external validation to a gravimetric standard, a set of filter samples from a multi-stage cascade impactor (e.g., a micro-orifice uniform deposit impactor or MOUDI) may also be desirable.

- **Online measurements of chemical composition:** Because chemical composition may substantially alter the optical response of the instrument, contemporaneous measurements of chemical composition can provide information on *why* the optical-to-mass response relationships of low-cost sensors vary. Online instruments such as the Aerosol Chemical Speciation Monitor (ACSM; Aerodyne, Inc.) can provide information on chemical composition of the bulk aerosol at hourly or better time resolution. A newer model of the ACSM also has the capability of measuring chemically-resolved particle size distribution.

- **Research-grade optical measurements:** Direct measurement of aerosol scattering, absorption, and total extinction may be valuable for understanding how shifts in the fundamental optical properties of the aerosol are changing over time. Basic instruments in this space include integrating nephelometers and soot absorption photometers (which include both filter-based and photo-acoustic measurements). Additionally, research-grade optical particle counters and optical particle sizers may be helpful in assessing the performance of lower-cost light-scattering particle counters.

- **Analysis of the relationship between humidity and particle growth –** Since the optical response of particles is so strongly dependent on humidity, it is essential that the humidity of the aerosol be quantified at the point of measurement. Even with simple humidity measurements, it may be possible to determine a statistical relationship that shows how humidity alters the response of a low-cost optical sensor. For additional insight, it may be helpful to develop an experimental apparatus that allows an artificially dried aerosol to be sampled in parallel with the ambient aerosol. For example, outside air could be passed through a diffusion drier into a well-mixed sampling chamber with well-characterized transmission efficiency. By comparing instantaneous readings of the ambient and dry aerosol, a humidity correction factor could be determined. However, it should be noted that the sample drying process should ideally not involve heating the sample, as heating could also result in loss of semi-volatile aerosol mass e.g., nitrate and some organics. Using this heated measurement as a reference could then overestimate the humidity correction factor estimated for the ambient aerosol.

Because the performance of particle sensors varies in space as well as time, ideally multiple calibration sites would be set up in India. A comparison of urban-background ("ambient") locations with traffic sites and rural areas would be valuable to understand how distinct source mixtures affect low-cost sensor performance. Moreover, regional differences are likely to be important in India. The key regional differences of importance are likely (i) the semi-arid Indo-

Gangetic plain vs. more tropical conditions in South India; and (ii) regions of the country with high impacts from particular source types (e.g., coal combustion products have a stronger impact in regions with a high density of thermal power plants).

Of course, the type of scientific instrumentation described above is relatively costly to purchase and maintain and requires specialty training. A practical starting point for a multi-site sensor characterization study might be to (i) establish several locations with a simple reference monitor and a "plug-and-play" testbed for evaluating multiple low-cost sensors, and (ii) equipping a small number of vans or trailers as relocatable test laboratories with the more specialized equipment that would rotate among the various test sites multiple times over the course of a year.

## 7. What are appropriate use-cases for low-cost sensors in India?

Air pollution measurement data are used around the world for a multitude of distinct use cases. To set the context for what might be the appropriate uses of low-cost $PM_{2.5}$ sensors in India, it is helpful to first note that there a large range of distinct applications that air pollution measurements are currently applied to. These applications range from regulatory compliance to scientific research to public information and awareness.

Many use cases for air pollution data involve a ***comparison.*** These might include comparison of measurements against a standard or health-based guidelines; comparison of air quality at multiple points in time; comparison of air quality at multiple points in space; or comparison of health effects among individuals with contrasting levels of personal exposure. For any measurement device – including a lower-cost sensor – to be useful for making such a comparison, it must be able to reliably and reproducibly detect any true concentration differences that are relevant for the comparison being made. The measurement device must also be robust to measurement artefacts that could (i) substantially interfere with the ability to detect any true differences that exist, or (ii) that could give rise to the spurious conclusion that a contrast in conditions exists when no such difference truly exists.

**Regulatory Compliance – Ambient Air Quality; Emissions Monitoring**
Air pollution measurements are routinely made around the world to verify that ambient air quality complies with applicable regulatory standards, such as 24-hour average or annual-average air quality standards. These measurements are generally undertaken by official bodies (e.g., State Pollution Control Boards in India; state and local air quality agencies in the United States) with a regulatory mandate to monitor ambient air quality. In some localities, major point emissions sources are also required to perform continuous stack/process emissions monitoring to validate compliance with emissions norms. Measurements for these compliance purposes often have significant legal weight, because of the legal consequences of non-compliance, and the potential litigation that can ensue when standards are violated. Because compliance is generally a binary outcome – either a concentration falls above or below a permitted value – high precision and accuracy is often a necessity in a regulatory context. Regulatory documents in many countries prescribe in great detail the technical requirements for measurements used for compliance, for example by specifying the allowed measurement technologies, siting requirements, QA/QC procedures, and data analysis techniques.

*Low-cost sensor outlook:* Given the legally defined consequences of regulatory monitoring, and the rigorous performance and reliability requirements that stem from such consequences, low cost sensors are not likely to be appropriate for the purpose of regulatory compliance in the long term.

**Long-Term Trends**

Policymakers often seek to understand how air quality responds over time to changes in human activity, technology, and policy. Because regulatory-grade monitors are often operated continuously under rigorously standardized conditions for long periods of time, they provide a valuable long-term record of how air quality has changed over time. For example, US EPA data demonstrate how national-average $PM_{2.5}$ concentrations in the USA declined ~ 41% between 2000 and 2017.

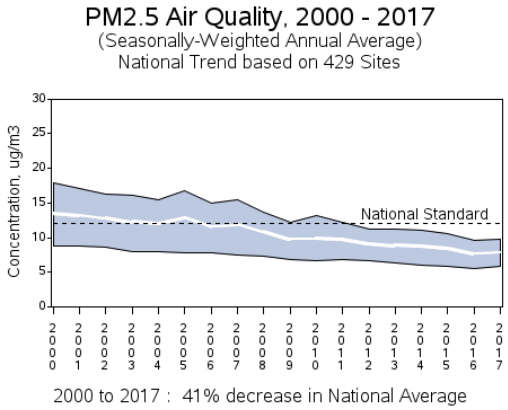


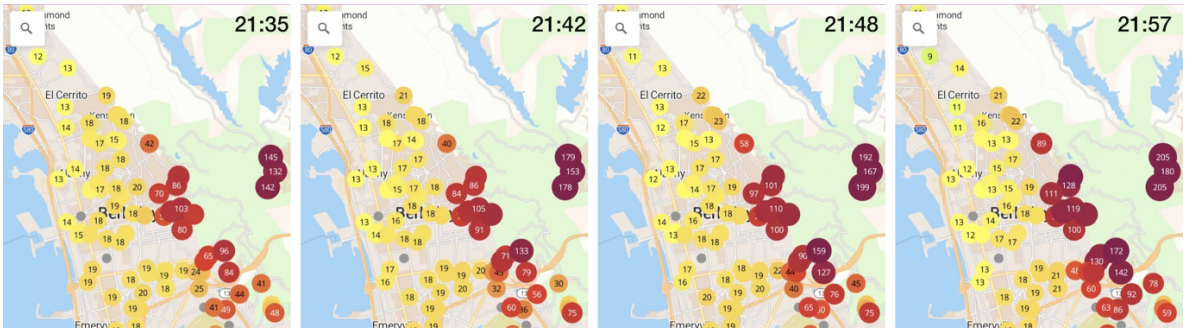

**Figure 8.** *Example of long-term trend data for ambient air quality based on US EPA monitoring. Source:* (www.epa.gov/air-trends/particulate-matter-pm25-trends)

*Low-cost sensor outlook:* Several key challenges exist for low-cost sensors in this application. First, the long-term durability of low-cost sensors is not well characterized. In the experience of our research group at UT-Austin, many low-cost sensors do not have a long lifetime under polluted conditions. For example, our evaluation tests of low-cost light-scattering $PM_{2.5}$ in New Delhi have frequently led to sensor failure with 3-12 months of continuous use. For some sensors, we have noted that failure has been gradual, and characterized by a slow and subtle decline in instrumental response, culminating in our determination that the sensor is no longer performing adequately. For other sensors, the failure is sudden – they no longer power on. In either case, currently available products are likely to be unsuitable for long-term monitoring of concentration trends. Second, annual changes in $PM_{2.5}$ are generally small as compared to the diurnal and seasonal variability, and thus may be challenging to quantify with acceptable uncertainty using current low-cost sensor devices. (However, the absolute concentrations in India are large.) Finally, sensor technology is currently evolving very rapidly. Accordingly, the sensors available even a few years from now may have very different performance characteristics than those available today.

**Intraurban variation in air quality**

Air pollution varies in space within cities. In general, locales near major emissions sources (e.g., traffic junctions, construction sites, industries) are more polluted than are sheltered urban-background locations. However, the degree to which any pollutant varies in space in a city depends strongly on (i) the mixture of sources that contribute to that pollutant's emissions, (ii) the atmospheric lifetime of the pollutant, (iii) whether the pollutant is an exclusively primary pollutant, or whether the pollutant is created through secondary chemistry of precursor emissions. Thus, a short-lived primary pollutant that is a unique marker for a single type of point source might be relatively more variable in space, while a long-lived pollutant that arises from multiple local and regional sources might be much less spatially variable. $PM_{2.5}$ falls much closer to this latter category of less spatially variable pollutants, while other species that are exclusively or predominantly vary much more sharply within cities (e.g., black carbon [BC], nitrogen oxides, and ultrafine particles [UFP]). For the case of New Delhi, for example, primary $PM_{2.5}$ emissions come from nearly a dozen unique types of emissions sources, and regional secondary formation is estimated to produce more than half of Delhi's $PM_{2.5}$ under typical conditions. In many cities, the range of spatial variability of $PM_{2.5}$ is relatively small. For example, Apte et al. (2011) found that levels of $PM_{2.5}$ in 2010 along some of Delhi's busiest arterial roads were only ~ 50-60% higher than ambient background concentrations, whereas BC and UFP number concentrations along these same routes were respectively 4 times and 8 times higher than background levels.[3]

While $PM_{2.5}$ levels are generally quite reasonably spatially homogenous, one notable exception is during episodes of smoke plumes – such as may be the case when plumes unevenly impact a city during episodes of crop burning or wildfire. Figure 9, below, shows an example from the PurpleAir network during August 2020 wildfires in the San Francisco Bay Area. Notable features in this map of Berkeley, California are (i) the very high density of sensors (multiple sensors in each neighborhood), (ii) the sharp spatial differences in air pollution between the hilly eastern and low-lying western part of the map – the elevated areas were inside a polluted atmospheric layer of wildfire smoke, while the low-lying areas were not, and (iii) the rapid changes in $PM_{2.5}$ over the ~25 minute period shown here. The high consistency among multiple monitors with each of the two distinct areas is also quite notable, which lends confidence to the notion that these low-cost sensors have good unit-to-unit precision. While this example speaks to the value of being able to distinguish between two neighboring areas with sharp concentration differences, it is worth emphasizing that in most cities, these sharp gradients arise during exceptional events, and are not routine occurrences.




[3] Apte JS, Kirchstetter TW, Reich AH, Deshpande SJ, Kaushik G, Chel A, Marshall JD, Nazaroff WW. 2011. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. *Atmospheric Environment* 45, 4470-4480.

**Figure 9.** Example of a wildfire smoke episode in the San Francisco Bay Area. August 2020.

*Low-cost sensor outlook:* With respect to low-cost sensing of spatial gradients in $PM_{2.5}$, a particular challenge arises precisely because the true $PM_{2.5}$ concentration gradients within many cities are not so large relative to the measurement uncertainty of low-cost sensors. Thus, a better application of low-cost sensors is for sensing larger spatial gradients in $PM_{2.5}$. Broader spatial patterns (e.g., variation within a region) may be a more appropriate initial application of low-cost sensor networks. For example, a regional network encompassing representative *urban and rural* areas of North India could be effective for detecting regional-scale events, such as long-range pollutant transport from dust storms, meteorological stagnation episodes, and widespread crop burning. Finally, given the low-cost of many sensors, it is worth exploring the idea of locating multiple sensors at each sampling location. If three or five sensors detect an anomalous pollution hotspot at a given place or time, the confidence in the determination of a "hotspot" would be much greater than if a single sensor was used.

## Public Information

Ambient air quality measurements are used in many environments for providing official or unofficial guidance about the health risks associated with a given level of air quality. The predominant public health impact of fine particulate matter arises due to the chronic diseases that are generated after long-term exposure (e.g., cardiovascular and respiratory diseases, cancers). Yet air pollution also has important short-term impacts, especially for susceptible populations such as children, asthmatics, and the elderly. Timely guidance can provide useful information for such subpopulations, especially when there are actions that may be easily taken (e.g., staying indoors to protect against severe ozone episodes).

### *Air Quality Index*

Public information can take a variety of forms. One commonly-employed format is an air quality index (AQI) that assigns hourly or daily air quality measures to a range of different categories that correspond to varying levels of health-protective advisories (e.g., good / poor / severe). The AQI is also often reported to the public on a numerical scale. On one hand, the broad concentration ranges that correspond to a given health advisory suggest that an AQI system could be reasonably robust to measurement uncertainty. On the other hand, the dichotomous categorization of air quality at the breakpoint between distinct advisory level – and the sharply differing public information guidance given at distinct levels – suggests that AQI systems also require accurate and precise measurements to operate effectively. For example, the United States EPA recently determined that PurpleAir sensors frequently miscategorized the true AQI category during wildfire smoke episodes.[4] Finally, it should be emphasized that AQI schemes differ dramatically from location to location, such that "satisfactory" air quality in one setting might be considered "poor" in another (see Figure 10 below).

[4] Johnson, K., A. Holder, S. Frederick, G. Hagler, AND A. Clements. PurpleAir PM2.5 performance across the U.S.#2. Meeting between ORD, OAR/AirNow, and USFS, Research Triangle Park, NC, February 03, 2020. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=CEMM&dirEntryId=348236

*Low-cost sensor outlook:* Given the uncertainty in low-cost sensor measurements, the idea of representing air quality with a set of categorical variables (e.g., colors) is appealing. A particular challenge for low-cost sensors arises given the inherent uncertainty and bias in many sensor readings: while the changeover from one color and its associated guidance actions (e.g., "stay indoors", "safe to play outdoors") is supposed to happen at a single fixed concentration, an incorrect sensor reading could lead to the wrong guidance being made. Careful thought must be given to risk communication in this context.

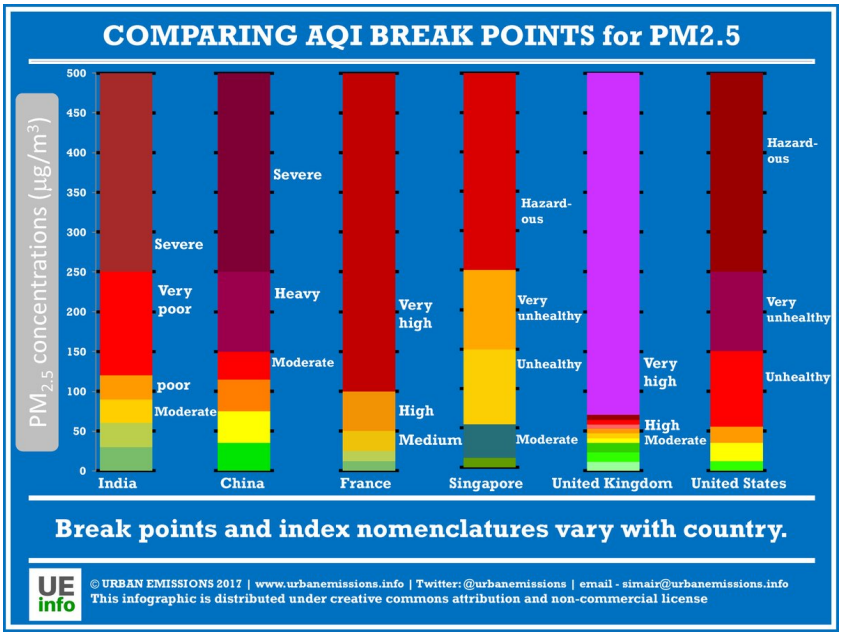



**Figure 10.** Comparison of air quality index scales for various countries (*Source:* Dr. Sarath Guttikunda, UrbanEmissions.Info)

***Temporal Comparisons***

Even without the use of an AQI scale, measurements may provide useful information about how air pollution varies at a single location over time. For example, how polluted is it today versus yesterday? Given that air pollution is invisible – or put more precisely, visibility has only a weak relationship with air quality – the ability to make day-to-day or hour-to-hour comparisons of air quality can be helpful for developing a stronger public awareness around air pollution.

*Low-cost sensor outlook:* In general, low-cost $PM_{2.5}$ sensors do adequately track the trends in air quality, and they can be reasonably used to answer questions like "is it relatively clean or polluted today?" or "is it much more polluted today than yesterday?". With the caveat that the calibration of a sensor does change somewhat by hour of day or day-by-day (see Figs 6-7), a low-cost sensor is likely to be very useful in providing personalized information about how air pollution varies over time at a given location. For example, Figure 9 illustrates a scenario in which $PM_{2.5}$ concentrations dramatically increased (by +50 µg $m^{-3}$ or more) across a neighborhood over a very short period of time.

**Citizen Science**

***Personal / indoor air quality***

While conventional air pollution instrumentation remains far outside of the range of most ordinary citizens, lower-cost sensors have proliferated as consumer devices. What do people do with these sensors? For many users, a first test of one's air quality sensor might be to conduct a set of manipulation experiments to answer questions such as: "how does air quality change in my home when I cook?"; "what happens to particle concentrations when I turn on my indoor air cleaner?"; or "how do particle levels change when I open my windows?". In each of these cases, a relative comparison in air quality is being made in response to manipulating some factor in the operation or use of one's home. Often, one can gain a strong intuition about what causes PM levels to change in a home even with a relatively inaccurate low-cost sensor.

> *Low-cost sensor outlook:* Low cost sensors are ideally suited to this type of home experimentation, which generally only requires that a sensor be accurate in a relative sense, rather than an absolute sense.

***Advocacy / environmental campaigning***

The use of low-cost PM sensors has proliferated among environmental advocates around the world over the past few years. To the extent that the goal of the user is to qualitatively demonstrate that the level of pollution is high or extreme, a low-cost sensor may be sufficient. However, even a sensor that has received some attentive calibration may not be sufficient for making a robust determination that *quantitative* concentrations fall above or below some threshold concentration (e.g., a regulatory standard), especially under very humid conditions (as is common in North India's most polluted winter months). Thus, low-cost sensors should be approached with care for this application.

**Epidemiological studies**

Environmental health and epidemiological studies come in a great diversity of different study designs (e.g., cohort, case-control, panel, time-series, cross-sectional, etc...). They also have a corresponding diversity in how exposure gradients are introduced (e.g., within-city, between-city) and measured (e.g., central site monitoring, home-address monitoring, personal measurement). However, one broad generalization is that many epidemiological studies rely on the ability to detect relative differences in health status that correspond with relative differences in exposure. For such studies, a consistently biased and reproducible exposure metric may be adequate. Low cost sensors thus ought to be considered as candidate tools used for exposure assessment in future health studies in India, especially given the paucity of other available measurements in India.

## 8. Strategic considerations: Low-cost sensors in broader context

In the academic settings of American and European air pollution research, a commonly heard turn of phrase is that "low-cost sensors are only low-cost if you don't account for the cost of your time." As this report has highlighted, there are numerous technical challenges for low-cost sensors that make them difficult to effectively deploy – and their data difficult to interpret and act-on – without a large-scale complement of technically sophisticated labor. Some of the key knowledge-and-skillsets required include a rich understanding of aerosol science, the ability to use specialized scientific grade instruments to characterize sensor performance, the ability to

manage large datasets, skill in computer network configuration and remote device management, a rigorous understanding of statistics (especially multivariate regression and time-series statistics), and a honed ability to make carefully-informed and -considered decisions on the basis of ambiguous results. In the experience of our research group at the University of Texas, it is difficult even in a well-resourced setting to assemble a team with this full set of capabilities. In the Indian context, while labor is comparatively less expensive, the pool of scientifically and technically qualified personnel is quite limited. If that pool of potential personnel does not dramatically expand, a worthwhile strategic question is whether the talents of these individuals are best deployed on characterizing a new generation of lower-cost sensors, or rather in deploying proven (but more expensive) conventional techniques at scale.

More broadly, it may be useful to draw a conceptual distinction between those applications where existing regulatory/scientific grade air sensors would be usefully and feasibly deployed (if not for cost barriers), and those applications where it would be logistically or practically impossible to deploy conventional measurement technologies (regardless of cost), but for which smaller, low-powered sensors enable transformational new insights that were not possible with prior monitoring technologies.

An example of the former case might include baseline ambient air quality monitoring for cities. In that situation, low-cost sensors might at best serve as a short-term stopgap until long-term monitors could be deployed. For example, even with the uncertainties associated with low-cost sensors, it would likely be both feasible and worthwhile to rapidly deploy a “starter kit” of a small number of replicate sensors to a representative ambient site in all Indian cities with more than 500,000 inhabitants. Even if it were desirable to replace uncertain low-cost measurements with more robust monitors within a few years, the insights gained from constructing this type of comprehensive network would likely be helpful.

An example of the latter application might be providing affordable in-home air monitoring to asthmatics, the elderly, and other sensitive subgroups of the population. Clearly, regulatory techniques would never be capable of providing personalized in-home data to this subset of the population, and even imprecise low-cost sensor data could provide useful, actionable qualitative information.

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